



ANOMALOUS GAUGE-BOSON COUPLINGS AT HADRON SUPERCOLLIDERS

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Abstract

We discuss anomalous gauge boson couplings at hadron supercolliders. We review the usual description of these couplings, as well as the studies of a strongly interacting electroweak symmetry breaking sector. We present an effective field theory formulation of the problem that relates the two subjects, and that allows a consistent and systematic analysis. We end with some phenomenology.

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1 Introduction

The main reason for building hadron supercolliders like the SSC or the LHC is to study the mechanism that breaks electroweak symmetry. There are many possibilities for this, and each one has distinctive signals. The simplest one is the minimal standard model with a Higgs boson, in which case the goal would be to find this particle. Typical technicolor models contain a large number of particles that should be found by these colliders; the case of the technirho has been studied most. Similarly, other possibilities like supersymmetry should have several particles within reach.

An interesting question is whether any of these new particles will be within the reach of the SSC/LHC. In anticipation that all new particles could lie just out of reach, many studies have been undertaken to extract information on electroweak symmetry breaking from its indirect effects. There are two fields in the literature that address this issue. One goes by the name of “anomalous gauge-boson couplings”, and the other one is known as “strong longitudinal gauge-boson scattering”. In this talk we will present an effective field theory formulation of the problem, that relates the two subjects and that allows a consistent and systematic study of anomalous couplings.

2 Anomalous Couplings

Conventional studies of anomalous couplings start from the Lagrangian¹

$$\begin{aligned} \mathcal{L} = & -ig_V \left[g_1^V (W_{\mu\nu}^\dagger W^\mu - W^{\dagger\mu} W_{\mu\nu}) V^\nu + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} \right] \\ & + a_c (W_\mu^+ W_\mu^-)^2 + \dots \end{aligned} \tag{1}$$

where V is either a photon or a Z -boson, and \dots stands for all other terms that we have not written.

There are several questions that arise when this Lagrangian is used. The first one is that it is not obviously $SU_L(2) \times U_Y(1)$ gauge invariant.² Although this has caused some confusion in the literature, it is *not* a problem, as was recently emphasized by Burgess and London.³ The reason why this is not a problem is that this Lagrangian is the unitary gauge version of an explicitly gauge invariant equivalent Lagrangian. For practical applications to supercolliders, it turns out to be useful to work with the

explicitly gauge-invariant version. In particular, because this permits the use of the equivalence theorem to simplify the calculations.

Another issue that is not clear in Eq. (1), is the question of how many independent anomalous couplings there are (the \cdots), and if there is a hierarchy amongst them.

The use of Eq. (1) also creates problems at the one-loop level. For example, the standard model at one-loop generates some of the “anomalous” couplings and one needs a procedure to separate these contributions from others due to electroweak symmetry breaking. Also, the Lagrangian of Eq. 1 is not renormalizable, and no procedure has been specified to treat the divergences that arise beyond tree-level. Some authors have addressed this problem at the practical level by introducing form factors.¹ Doing so, further complicates the issue of counting and classifying the independent couplings.

We answer all these questions by using an effective (“chiral”) Lagrangian supplemented with the rules of chiral perturbation theory.⁴ This gives us an effective field theory formalism that allows a systematic and consistent study of these issues.

3 Strongly Interacting V_L

Much work has been done under the heading of strongly interacting longitudinal W ’s and Z ’s ($\equiv V_L$).^{5,6} Perhaps the most important concept in this field is that of “enhanced electroweak strength”. In the standard model, the amplitude for WW scattering is proportional to g^2 multiplied by polarization vectors for the W ’s. If one looks at the longitudinal polarization (in a frame where $E/M_W \gg 1$), one finds that some of the g^2 terms are now multiplied by M_H^2/M_W^2 . For a very heavy Higgs boson, these terms are thus much larger than the usual g^2 terms, they are of “enhanced” electroweak strength.^{5,6} In the standard model without a Higgs boson the Higgs mass is replaced by the energy of the W ’s. One then has terms of order g^2 , terms of order $g^2 s/M_W^2 \sim s/v^2$, $v \approx 250$ GeV, and also terms of order $(s/v^2)(s/\Lambda^2)^n$ where Λ is the scale at which the effective theory breaks down. The terms that grow with s are of enhanced electroweak strength at high energies. It is these terms that are of interest at hadron supercolliders. When one is only interested in extracting these terms, one can resort to the equivalence theorem and replace the gauge bosons W, Z with their would-be Goldstone bosons w, z even inside loops.^{5b,5c,7}

By computing V_L scattering in the standard model, one is able to place “unitarity” bounds on the Higgs mass.^{5a,5b} At high energies, the partial waves are proportional to M_H^2 , and thus if M_H is too large, they violate the unitarity condition $|a| \leq 1$. In the absence of the Higgs boson, these partial wave amplitudes grow like s , violating the unitarity bound at about 2 TeV. One expects the physics associated with electroweak symmetry breaking to come in at this scale (or below). In the case where no new particles lie below this scale, the study of anomalous couplings consists of looking for deviations of the leading s behavior of amplitudes at high energies. One can think of this as a general way of taking the infinite mass limit of the standard model Higgs.

4 Effective Lagrangian

To construct the effective Lagrangian we introduce the Goldstone bosons w^\pm , z through the matrix $U = \exp(i\vec{\tau} \cdot \vec{w}/v)$, and the gauge fields through the covariant derivative

$$D_\mu U = \partial_\mu U + i\frac{g'}{2}B_\mu\tau_3U - i\frac{g}{2}UW_\mu$$

We also have the field strength tensors

$$\begin{aligned} W_{\mu\nu} &= \frac{1}{2}\left(\partial_\mu W_\nu - \partial_\nu W_\mu - i\frac{g}{2}[W_\mu, W_\nu]\right) \\ B_{\mu\nu} &= \frac{1}{2}\left(\partial_\mu B_\nu - \partial_\nu B_\mu\right)\tau_3 \end{aligned} \tag{2}$$

The lowest order effective Lagrangian is:⁸

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\text{Tr}D_\mu U^\dagger D^\mu U + \dots$$

where \dots stands for the usual gauge boson kinetic terms, couplings to fermions, and gauge fixing terms. This is the term that gives the W and Z their mass as can be seen immediately in unitary gauge ($U = 1$). This is a non-renormalizable Lagrangian, and divergences that occur at the loop level are handled in the usual way by chiral perturbation theory. At tree-level, this Lagrangian produces amplitudes of order E^2 in an energy expansion. At one-loop, the divergences that appear are of order E^4 , and are absorbed by renormalization of the next to leading $\mathcal{O}(E^4)$ effective Lagrangian.

By looking for the most general form consistent with a global $SU(2) \times U(1)$ symmetry spontaneously broken to $U(1)$ (but conserving CP), Longhitano found⁸ that

the next to leading order Lagrangian contains 13 terms (and the leading order Lagrangian contains an extra term, $\Delta\rho$). We will not use this general Lagrangian, but instead we will introduce an additional assumption: that there is a custodial $SU(2)$ in the physics of electroweak symmetry breaking. That is, that the global symmetry is $SU(2) \times SU(2)$ broken to $SU(2)$. This amounts to requiring that the additional “custodial” $SU(2)$ be broken only by g' and by the difference in fermion masses.

This is a reasonable assumption, which is true both for the minimal standard model and for common extensions such as technicolor. It is also a consistent assumption for experiments at supercolliders. The reason is that at the very high energies of these machines we can concentrate only on those terms of enhanced electroweak strength as explained before. The counterterms needed to renormalize the loop diagrams of enhanced electroweak strength respect this custodial $SU(2)$. Note that this is *no longer valid* for low energy experiments, such as the ones that will be carried out at LEP2. In that case the distinction between electroweak strength and enhanced electroweak strength is not meaningful, and for consistency one must keep the full counterterm structure that appears at one-loop.

The next to leading order effective Lagrangian is:⁹

$$\begin{aligned} \mathcal{L}^{(4)} = & \frac{v^2}{\Lambda^2} \left\{ gg' L_{10} \text{Tr} \left(U^\dagger B_{\mu\nu} U W^{\mu\nu} \right) \right. \\ & - ig L_{9L} \text{Tr} \left(W_{\mu\nu} D^\mu U^\dagger D^\nu U \right) - ig' L_{9R} \text{Tr} \left(B_{\mu\nu} D^\mu U D^\nu U^\dagger \right) \\ & \left. + L_1 \left[\text{Tr} \left(D_\mu U^\dagger D^\mu U \right) \right]^2 + L_2 \left[\text{Tr} \left(D_\mu U^\dagger D_\nu U \right) \right]^2 \right\} \end{aligned} \quad (3)$$

The scale Λ is determined by the mass of the lightest particle in the symmetry breaking sector, and in any case it is $\Lambda \lesssim 4\pi v$. The next to leading order terms in the effective Lagrangian have been normalized by v^2/Λ^2 ; this reflects the fact that they appear as the heavy physics associated with the scale Λ is integrated out. With this normalization, the L_i are all expected to be $\mathcal{O}(1)$. By going to unitary gauge one can easily see what are the contents of this Lagrangian. The first line contains a correction to the Z self energy that has been thoroughly discussed:¹⁰

$$L_{10}'(M_Z) = -\pi S$$

when we take $\Lambda = 4\pi v$. The next line contains the lowest order anomalous three gauge boson couplings.^{11,12} The more common κ_γ , κ_Z and g_1^Z are simply some linear

combinations of L_{9L} , L_{9R} and L_{10} ;¹²

$$g_1^Z - 1 \sim \kappa_V - 1 \sim \mathcal{O}\left(g^2 L_{9L,9R,10} \frac{v^2}{\Lambda^2}\right)$$

Finally, the last line contains the lowest order anomalous four gauge boson couplings. There are only two of them: L_1 and L_2 .¹³

The bare L_i coupling constants that appear in the Lagrangian are used to absorb the divergences generated by $\mathcal{L}^{(2)}$ at one-loop. It is the renormalized running couplings $L_i^r(\mu)$ that are physical and can be related to observables. A convenient renormalization scheme has been defined in the literature,⁹ and dimensional regularization is typically used. Once again, since we are only interested in terms of enhanced electroweak strength, there is no need to renormalize the electroweak gauge sector. This is the reason why we do not need custodial $SU(2)$ breaking counterterms like $\Delta\rho$ (or “T”).

Some of the anomalous couplings in Ref. 1a, namely those with λ_V , are not present in the effective Lagrangian at order E^4 . These terms appear at the next order, E^6 , and are thus expected to produce much smaller effects (suppressed by $\sim s/\Lambda^2$) than the κ_V terms. They are of the same order as the slope terms introduced when κ_V is modified with a form factor. Within our assumptions, these terms in Eq. (1), should have been normalized by Λ^2 instead of M_W^2 . The energy expansion breaks down at some scale near 2 TeV, where all the terms become equally important.

We have emphasized that the $L_i^r(\mu)$ couplings are naturally of order one. A value much larger than 1 of one or more of these couplings, would indicate that the formalism is breaking down at much lower energies than it should. This is associated with the presence of some new, relatively light, particle beyond the standard model. In our Lagrangian, we have explicitly included all the known particles in the standard model and we have assumed that any new particles associated with electroweak symmetry breaking are heavy: of order a few TeV. The effect of these heavy particles is only felt indirectly through the anomalous couplings. If there are some relatively light particles, for example a 300 GeV Higgs boson, then the formalism has to be modified to include the light Higgs explicitly in the Lagrangian. For this example, there exists another formulation of the effective Lagrangian that one could use, namely that in which the symmetry breaking is linearly realized.² For studies at the SSC it is reasonable to assume that there are no such light particles, since they would be discovered directly. For studies at lower energy machines like LEP2 this is not the

case. A 300 GeV Higgs boson would still not be seen directly and the study of its indirect effects remains interesting. Of course this is not the only possibility, there could be, for example, a 300 GeV vector resonance. To study that case at LEP2 one could use an effective Lagrangian that contains this field explicitly.¹⁴

5 Phenomenology

The explicit gauge invariance of Eq. (3) allows us to use the equivalence theorem to simplify the calculations. As long as we are only interested in terms of enhanced electroweak strength, we can compute with the $\mathcal{O}(E^4)$ terms presented here, replacing all the vector bosons with their corresponding would-be Goldstone bosons. The only exception is for vector bosons in the initial state since these couple to light fermions. For $q\bar{q}$ annihilation we must keep the “initial” vector boson. For vector boson scattering, the effective luminosity of transverse gauge bosons in the protons is much larger than that of longitudinal gauge bosons.¹⁵ In practice, we find that for energies above ~ 500 GeV, the longitudinally polarized initial states completely dominate the cross sections.⁹

There are three mechanisms to produce vector boson pairs at hadron colliders. Each of them is sensitive to different anomalous couplings. The largest source of vector boson pairs is $q\bar{q}$ annihilation.¹⁶ This process is sensitive to anomalous three gauge boson couplings L_{9L} and L_{9R} (also to L_{10} but not in terms of enhanced electroweak strength).^{9,12} The vector boson fusion mechanism is sensitive to all the anomalous couplings, but only to L_1 and L_2 at the enhanced electroweak strength level.^{9,13} Finally, gluon fusion is not sensitive to any of the anomalous couplings we have discussed (to $\mathcal{O}(E^4)$), but it is to anomalous couplings of the top-quark $g_A - 1$.¹⁷ It has been argued in the literature that the vector boson fusion process can be separated experimentally from the other two by tagging one forward jet.¹⁸

For our numerical studies we will take $\Lambda = 4\pi v$, in accord with our assumption that there are no new particles below a few TeV.

One of the couplings of the effective Lagrangian has already been measured. A fit to all data by Altarelli¹⁹ translates into $L_{10}^r(\mu) = 0.5 \pm 1.6$ at $\mu = 1500$ GeV. This one doesn’t contribute to the processes of interest at the SSC (enhanced electroweak strength production of V_L pairs). The UA2 collaboration has reported:²⁰ $-2.2 \leq \kappa_\gamma - 1 \leq 2.6$. This translates into $|L_9| \lesssim 900$. This is expected to improve²¹ by a

factor of 2 at the Tevatron. Similar results are expected from LEP2.¹ Within our framework this means that there will not be any significant bounds on L_9 before the SSC/LHC. There are no present bounds on the anomalous four-gauge boson couplings.

We have done a very crude phenomenological analysis, in which we *assume* that it is possible to measure the polarization of the vector bosons. We have computed the contribution of the anomalous couplings to the integrated cross section for $0.5 < M_{VV} < 1.0$ TeV, and defined the contribution to be observable if it induces at least a 50% change in this integrated cross section. With this we find that:⁹

The $W_L Z_L$ channel will be sensitive to $L_{9L}^r(\mu) \lesssim -3.5$ or $L_{9L}^r(\mu) \gtrsim 2.5$. If we assume that it is not possible to extract the longitudinal polarization, the change in the rate is always less than a few percent.

The $W_L^+ W_L^-$ channel will be sensitive to a combination of L_{9L} and L_{9R} if $L_9 \lesssim -4.0$ or $L_9 \gtrsim 3.0$. Again, this is assuming that all backgrounds can be eliminated and polarizations measured.

The $W_L^+ W_L^+$ channel is sensitive to a combination of L_1 and L_2 if $|L_1| \gtrsim 1$ or $|L_2| \gtrsim 1$.

To understand the possible significance of these numbers it is instructive to compare with previous studies on anomalous three gauge boson couplings at the SSC that considered all polarizations. Kane, Vidal and Yuan²² found that the SSC would be sensitive to $|L_9| \gtrsim 25$ and Falk, Falk and Simmons¹² found that the SSC would be sensitive to $L_{9L} \lesssim -16$ or $L_{9L} \gtrsim 7$ by looking at the WZ channel. This result is consistent with our estimate. They also found that the SSC would be sensitive to $L_{9R} \lesssim -119$ or $L_{9R} \gtrsim 113$ from the $W\gamma$ channel. In this case the bound is weaker because the final state can have at most one longitudinal polarization, so the amplitude can only grow as \sqrt{s} . In the WZ channel, the leading term in the amplitude grows like s .

We have argued that if there are no new light particles, the L_i should be of order one and not significantly larger. This implies that to obtain meaningful bounds on anomalous three gauge boson couplings at the SSC, an effort to separate the transverse background is necessary. We have not studied the feasibility of this separation, and more detailed phenomenology is clearly needed. On the other hand, the $W^+ W^+$ channel seems to be a very promising one to place significant bounds on anomalous

four gauge boson couplings. This channel is particularly useful because it is the one with the lowest backgrounds, as has been emphasized in the literature.²³

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